EXPERIENCE IN TURBULENCE IN HYDRAULIC STRUCTURES

HAROLD M. MARTIN,
WILLIAM E. WAGNER

BIRO OF RECLAMATION UNITED STATES DEPARTMENT OF THE INTERIOR DENVER, COLORADO — USA

This paper indentifies the types of turbulent flow experienced in high-head hydraulic structures and appurtenances. Turbulent flow in a complex outlet works structure creating severe vibration was studied in the laboratory. Measurements taken and method of analysis of data leading to an improved structure are presented. Experience with turbulence-iduced vibration in high-head valves is related. Model-prototype verification date are included. Model and prototype studies of medium-head stilling basin are described in moderate detail. Transient pressure measurements made in laboratory studies are reconciled with prototype observations including cavitation noise and vibration. Finally, laboratory studies of pressure variations in a high-head penstock Y-branch are described together with prototype observations.

The paper illustrates the importance of obtaining all possible data in studies of turbulence in high-head structures and demonstrates limitations of pressure and vibration measurements. Velocity and turblence surveys will undoubtedly improve the understanding of turbulent flow as improved techniques become available.

Ce rapport identifie les types d'écoulement turbulent trouvés dans les structures hydrauliques de haute chute et leurs ouvrages annexes. L'écoulement turbulent dans une structure complexe d'ouvrage de sortie, qui produit une vibration sévère, fut etudé dans le laboratoire. Les auteurs donnent les mésures prises et la méthode utilisée pour analyser les données en vue d'améliorer la structure. L'expérience avec la vibration induite par la turbulence dans les vannes de réglage de haute chute est exposée. Les données verifiées sur modèle et sur place sont comprises. Des études sur modèle et sur place d'un bassin d'amortissement de moyenne chute sont décrites en quelques détails. Les mesures de la pression transitoire effectuées dans les recherches en laboratoire sont accordées avec le bruit et la vibration de cavitatien. Enfin, les investigations en laboratoire des variations de la pression dans une conduite forcée bifurqué de haute chute sont décrites en jointe avec les observations du prototype.

Ce rapport explique l'importance à obtenir toutes les données possibles par les études de la turbulence dans les structures de haute chute et démontre les limitations des mésures de la pression et de la vibration. Suivant que les meilleures techniques commencent à se développer, les examens de la vitesse et de la turbulence augmenteront sans doute la connaissance de l'écoulement de haute chute.

INTRODUCTION

Turbulent flow is the result of the disintegration of eddies into a random pattern of mixing throughout the fluid. It is characterized by the presence of wandering vortices or eddies whose velocities are irregular and vary both in direction and magnitude. This intermixing of the fluid results in the dissipation of energy accompanied by pressure fluctuations which are intensified by abruptly changing a flow boundary, by submerging the jet, or by placing an obstacle, such as a baffle, in the flow path.

Fluid turbulence plays an important part in designing hydraulic structures. The intensity of turbulence may be influenced by the boundary roughness which must be considered in computing the head loss in a conduit or the capacity of conveyances. Turbulent eddies cause a submerged jet to expand laterally and serve to decrease the jet velocity. Turbulent motion in a hydraulic jump results in a relatively high loss of energy and becomes violent in reducing supercritical flow to nominal velocities which can be readily handled in natural or artificial channels without excessive erosion. Flow boundaries, if improperly designed, may establish zones of excessive turbulent eddies which cause large pressure fluctuations with accompanying vibration or cavitation in the system.

Since its inception in *1902*, the Bureau of Reclamation has built *158* storage dams with associated spillways, outlet works, and powerplant structures. In designing these control structures which may operate under head up to *500* feet and develop flow velocities in excess of *150* feet per second, many unusual flow problems are encountered in shaping the flow passages, controlling the flow, and dissipating the energy.

This paper presents several prototype experiences by the Bureau of Reclamation in which turbulence has significantly affected the operation of hydraulic structures, and describes the methods of analysis and the measures taken to correct or improve the flow and operational characteristics of the structures.

Turbulence, as discussed in this paper, refers to the largescale turbulent mixing experienced in a hydraulic jump or a zone of separation rather than the fine-grained turbulence found in flow between parallel boundaries.

VIBRATION IN CONTROL STRUCTURES

Keechelus Dam Outlet Works[1)]

Keechelus Dam was constructed over *40* years ago as a flood control and irrigation storage project on the Yakima River about 75 miles southeast of Seattle, Washington. Irrigation releases from the reservoir are made through a *11*-foot *10*-inch high horseshoe-shaped conduit, approximately *450* feet in length. Water enters the conduit through a vertical intake tower containing an inner cylindrical shaft and an outer annular passageway, separated by concrete walls, Figure 1.

Nine openings *4* feet high and about *3.2* feet wide at two levels, elevations *2415* and *2470*, form water passages through the inner cylinder wall. Flow through these openings is controlled by two *12*-foot-diameter cylinder gates operated from the gatehouse on top of the inner cylinder. Three guide walls, *120* degrees apart and extending vertically between the levels of the cylinder gates, separate the annular ring into three passageways and provide stability to the tower. One of the three walls is located on the outlet center line directly above the entrance of the outlet conduit. The other two walls are continuous between elevations *2430* and *2474*, except for *4*-foot high openings with bottom elevations of *2440* and *2448*.

The inlet to the gate tower is located opposite the outlet conduit and contains six *7*-foot high by *3*-foot-wide emergency slide gates separated by piers. Water is passed through the slide gates into the annular passageways, through the cylinder gates into the inner cylinder, and out through the outlet conduit whose invert intersects the inner cylinder at elevation *2424.3*. A vertical pier *2* feet thick and *11* feet long on the outlet center line divides the conduit entrance.

The outlet is designed to release a maximum flow of *3,950 cfs* under a head of *95* feet. The upper cylinder gate is used for regulation when the reservoir level is sufficiently high to release the required amount of water. Normal releases, however, are made through the lower cylinder gate.

Operation of the outlet works over the years has shown that excessive vibration in the gate structure occurs when the discharge is about *1,300* to *1,500 cfs*. The vibration was particularly severe when releases were made simultaneously through both lower and upper cylinder gates.

In *1950*, a *1* to *15* scale model of the intake tower and outlet conduit was constructed and tested to determine the cause of the vibration and to develop methods of reducing or eliminating it, Figure *2A*. The vibration characteristics of the prototype structure were evaluated qualitatively, because it was infeasible to obtain similarity for the physical properties of the model and prototype structures.

Initial observations of the model indicated that large random eddies and surges formed in the inner cylinder when water passed

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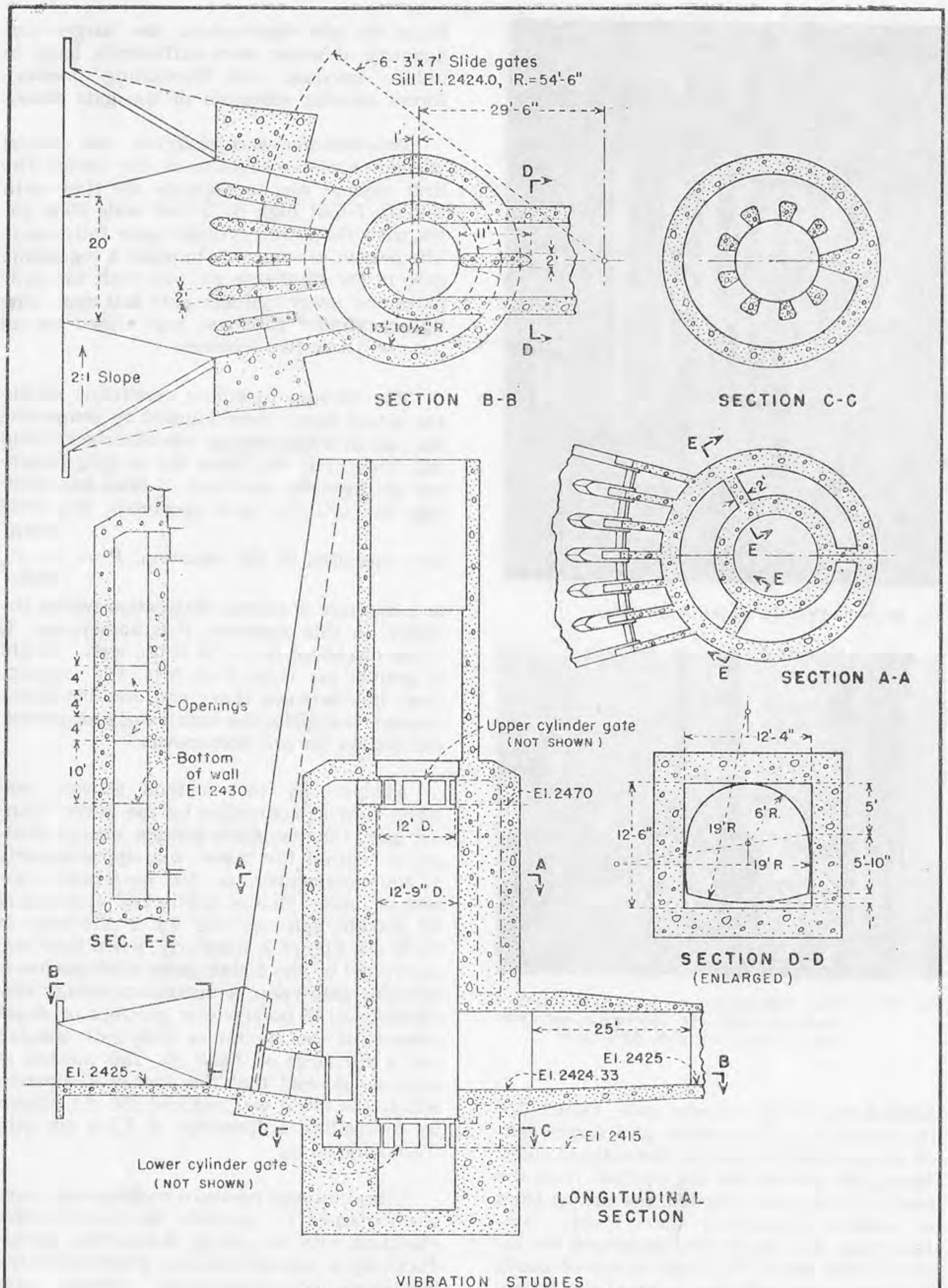
1) Bureau of Reclamation Report No. HYD-342, Hydraulic model study of the vibrations of Keechelus Dam Outlet Works-Yakima Project, Washington.



VIBRATION STUDIES

KEECHELUS OUTLET WORKS

Fig. 1

Fig. 2a — 1—15 scale model intake tower

Fig. 2b — Flow disturbance in model gate tower- - discharge 2720 cfs. Reservoir elevation 2520- -lower ring gate 50% open

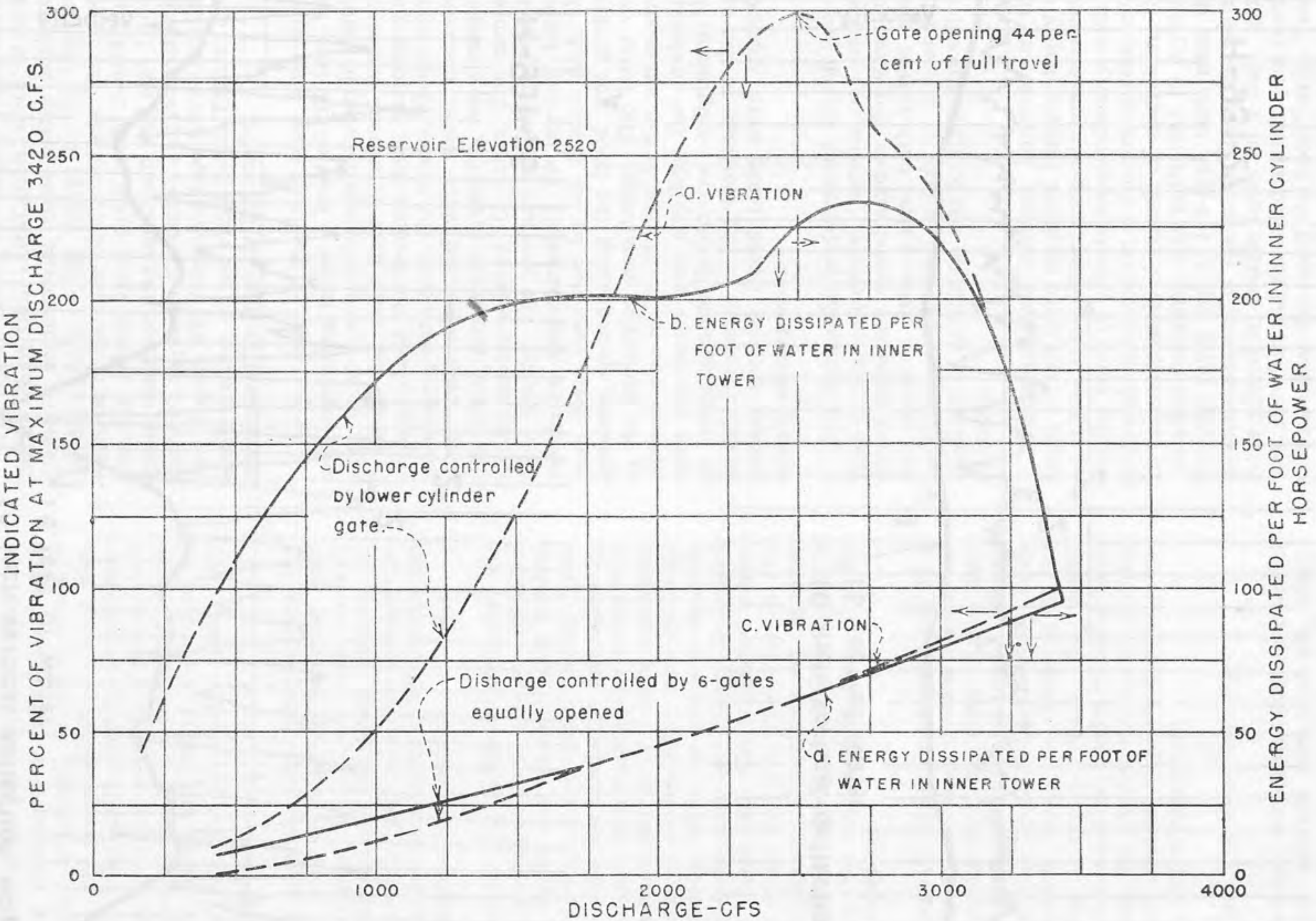
through the lower cylinder gate, Figure *2B*. The instability of the eddies and surges caused a fluctuation of flow into the outlet conduit. During the period that the outflow from the inner cylinder was retarded, the inflow from the annular passageway under nearly constant head was stored and increased the inner cylinder depth. With the increased depth of water in the cylinder, more of the inflow energy was absorbed, the eddies subsided, and the outlet discharge again increased. From the test observations, the surges and quantity of water were sufficiently large to induce unequal and fluctuating pressure forces causing vibration of the gate tower.

Two schemes were tested in the model without a major revision of the tower. The first scheme was to regulate the flow with the six 7-foot high by *3*-foot wide slide gates with the lower cylinder gate fully open. The second scheme was to place a regulating gate in the discharge conduit with the slide gates and lower cylinder gate full open. The upper cylinder gate was kept closed for all tests on these two schemes.

The varying turbulent conditions within the intake tower were studied by comparing the rate at which energy was absorbed within the inner cylinder. Since the surging indicated an unsteady condition of head loss through the cylinder gate apertures, this head loss was used in the equation, $P = \frac{QWh}{550}$, as a measure of energy dissipation within the tower. In this equation, P is horsepower, Q is the discharge in cfs, W is the water weight in pounds per cubic foot, h is the average head loss between inner and annular passageways, and *550* is the number of foot-pounds per second for one horsepower.

Analysis by this method showed that when flow as controlled by the lower cylinder gate, the maximum average energy dissipation within the tower was approximately *13,800* horsepower, or *230* horsepower per foot of inner cylinder depth, and occurred at *52* percent gate opening for a discharge of *2,700 cfs*, Figure 3. Similarly, when flow was controlled by the *6* slide gates with the lower cylinder gate open, a maximum energy dissipation of *97* horsepower per foot of depth occured at the maximum slide gate opening and a discharge od *3,600 cfs*. This method of analysis showed that the energy dissipation within the tower was reduced about *3.3* times by controlling a discharge of *2,700 cfs* with the *6* slide gates.

Vibration and pressure oscillograms were also obtained to correlate the model tower vibration with the energy dissipation. An inductivetype vibration meter, which measured frequency and displacement velocity, was fastened to the sheetmetal transition between the tower and exit conduit, Figure 2A.



VIBRATION STUDIES—KEECHELUS OUTLET WORKS

Vibration studies using lower cylinder gate and six slide gates to control discharge

Fig. 3

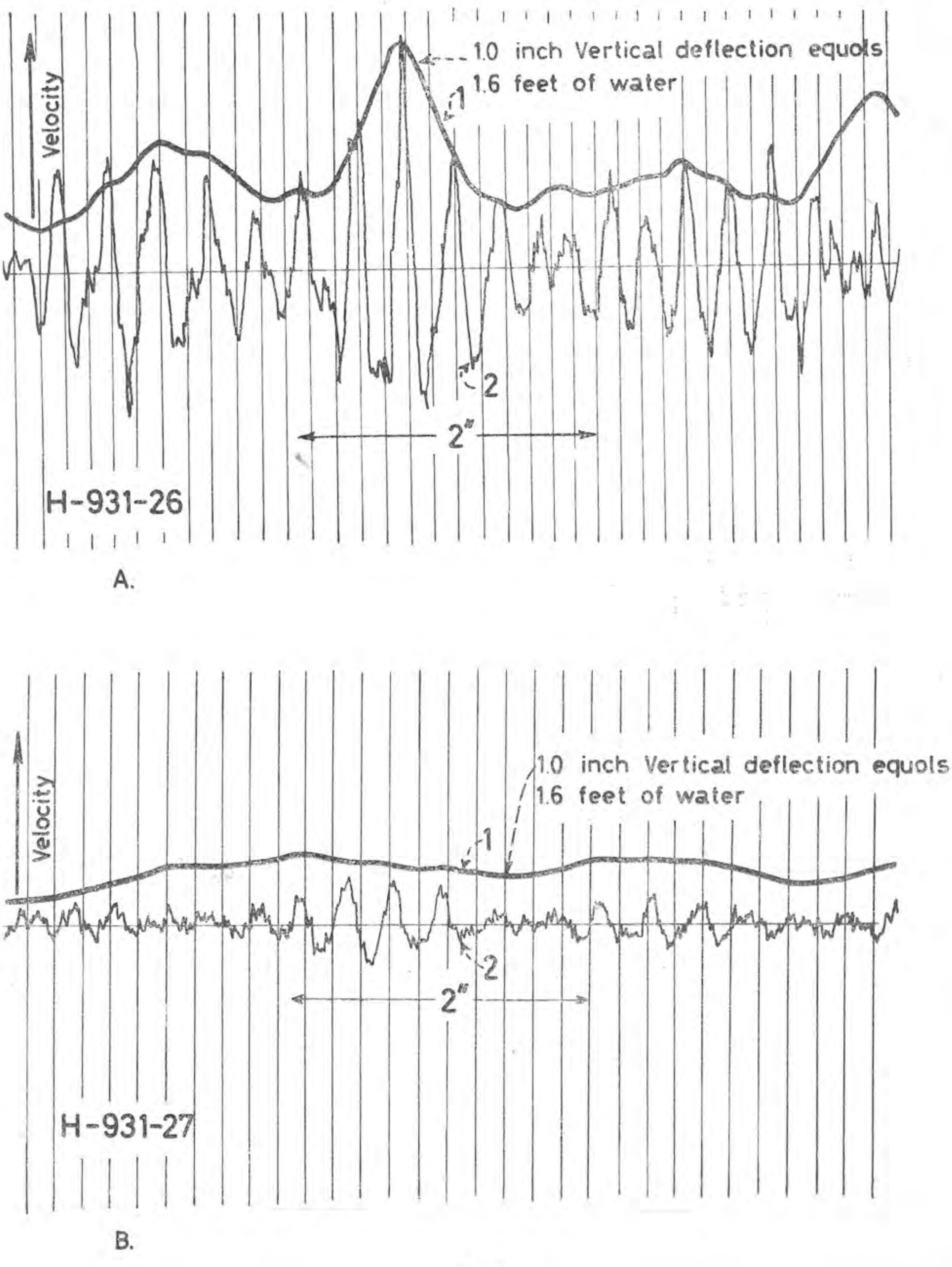

1.0 inch Vertical deflection equals
1.6 feet of water
Velocity
1
2
2"
H-931-26
A.
1.0 inch Vertical deflection equals
1.6 feet of water
Velocity
1
2
2"
H-931-27
B.

Fig. 4

The recorded vibration frequency and velocity of disceplacement of the model transition surface qualitatively represented the vibration characteristics of the prototype transition because of the difference in physical properties of the two structures. Traces of pressure variation on the transition invert were also transmitted to the oscillogram by a reactance-type pressure cell connected to a piezometer. Representative traces of the transition vibration for a discharge of *2,500 cfs* controlled by the cylinder gate and the *6* slide gates are shown in Figure 4.

The average trace amplitude (average velocity) was used to compare the slide gate control to that of the cylinder gate control, Figure 4. The percent indicated vibration for any gate opening is plotted as the average trace amplitude for that opening divided by the amplitude for the full opening.

Good correlation between indicated vibration in the tower and energy dissipated per foot of depth was obtained with control by the slide gates or the lower cylinder gate. The curves with the discharge controlled by the cylinder gate indicate that the tower will absorb maximum energy and have maximum vibration at approximately the same disharge and gate opening. With the discharge controlled by the *6* slide gates, the energy dissipated per foot of depth and the indicated vibration of the tower were a maximum at *100* percent gate opening. The indicated vibration with the cylinder gate control was found to be *4.8* times that for the slide gates at a discharge of *2,500 cfs*.

On the basis of these test results and as a temporary expedient until a more permanent means of regulation is provided, it was concluded that releases could be made through the outlet works using the emergency slide gates for control when the vibration in the tower became excessive. Since the model studies were completed, outlet releases have been less than *900 cfs* and the lower cylinder gate has been used for regulating service without objectionable vibration.

Hovell-Bunger Valves at Ross Dam

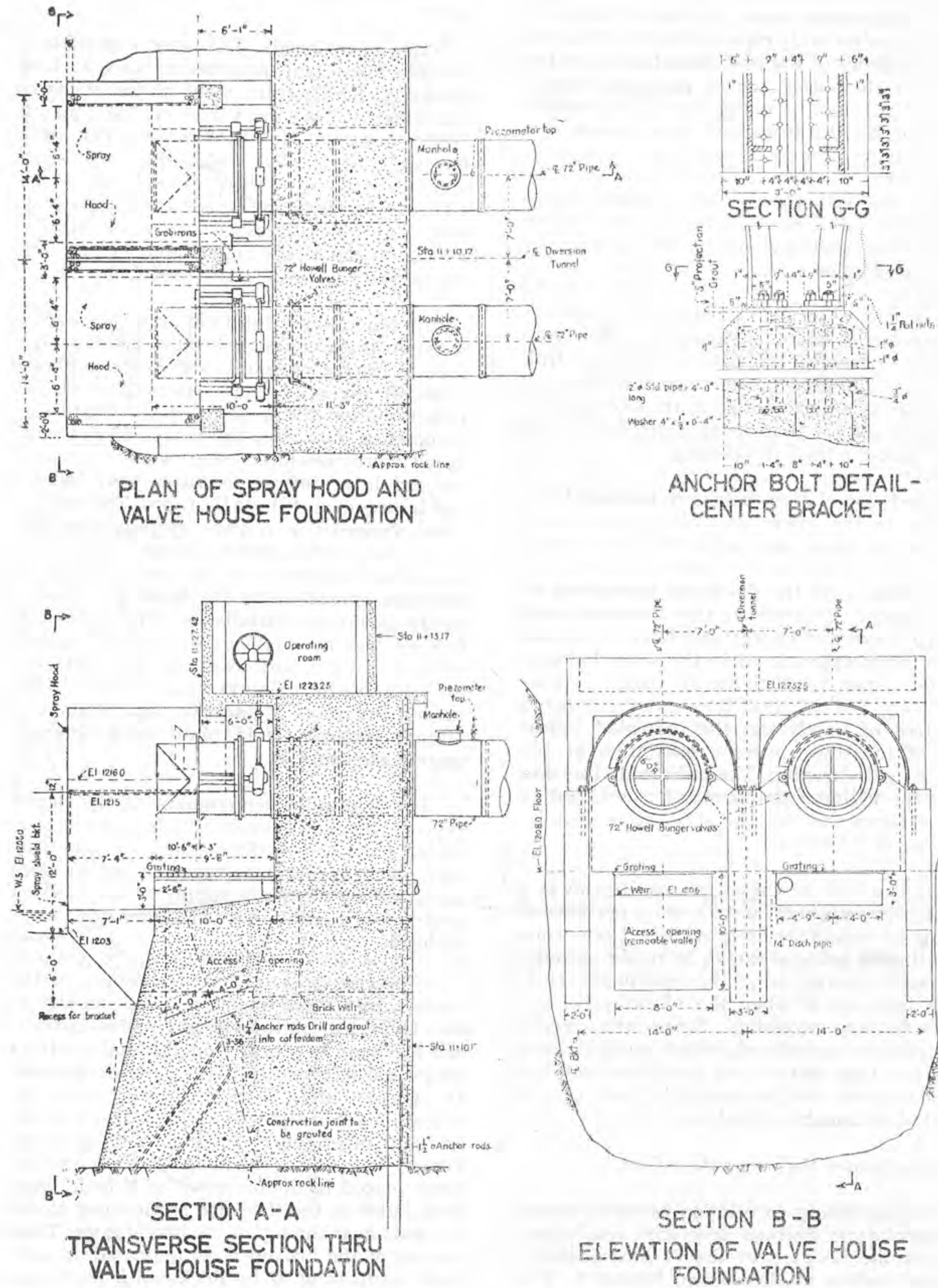
An interesting correlation between model and prototype average pressures was obtained on the hoods over the 72-inch Howell-Bunger valves at Ross Dam, Figure 5. The hoods were developed by model studies to prevent excessive, inherent spreading of the jet and to reduce objectionable spray, Figure 6A.

The spray hoods, developed specifically for the Ross Dam installation, were 12-foot-diameter semicircular steel plates anchored independently of the valves to the concrete walls on either side of the outlets. The hoods were of *1*-inch steel plate with *1—1/8*-inch shield plates on the upstream end and *1*-inch stiffener bands at the center and downstream end, Figure 6B. Pressure taps were installed along the top of the right hood, Figure 7, to correspond to those in the model.

At the time of the field tests, the valves were operating under a head of *200* feet. Results of the pressure tests are shown in Figure 7 where the solid lines represent prototype pressures and the broken lines indicate corresponding data from the model. Model pressures were measured with water manometers while prototype pressures were measured by mercury-filled »*U*« tubes. The comparison showed the average prototype pressures to be approximately *20* percent higher than those indicated by the model. Also, the pressure spread along the hood was greater in the prototype installation. The latter difference was no doubt due to the air mixing with the water and swelling the prototype jet, while air insufflation was negligible in the model. Pressures at the two taps in the upstream vertical shield plate were approximately atmospheric.

The hydraulic performance of the prototype valves was entirely satisfactory, as predicted from the model studies. No vibration was noted in either valve; both valves were receiving an adequate supply of air, and no evidence of cavitation was found in the valves or hoods.

Vibration was obvious, however, in the hoods which were mounted independently of the valves. Intermittent surges in pressure caused the hood to vibrate longitudinally with a noticeable deformation of the downstream end. In approximately *1* month of operation, the vibration intensity was sufficient to crystallize and sever ten *1—1/4*-inch bolts near the downstream end of the hood. The bolts, which were placed in double rows on *6*-inch centers, failed in the threaded section just inside the nuts near the top of the hood flange. Tests on one of the broken bolts indicated an average hardness of *97* by Rockwell *B* test or an approximate strength of *100,000* pounds per square inch, a fair grade of steel alloy.



PLAN OF SPRAY HOOD AND VALVE HOUSE FOUNDATION
Spray
Hood
Grabirons
72" Howell Bunger Valves
Manhole
Piezometer top
Sta 11+10.17
Diversion Tunnel
Approx rock line
SECTION G-G
ANCHOR BOLT DETAIL-CENTER BRACKET
Washer
SECTION A-A
TRANSVERSE SECTION THRU VALVE HOUSE FOUNDATION
Operating room
Spray Hood
Grating
Access opening
Brick Wall
Recess for bracket
Construction joint to be grouted
Approx rock line
72" Pipe
SECTION B-B
ELEVATION OF VALVE HOUSE FOUNDATION
72" Howell Bunger valves
Grating
Weir
Access opening (removable wall)
14" Disch pipe

Fig. 5

As a temporary solution, the broken bolts were fused to the hood flange by means of welding. The welded bolts remained intact until the Howell-Bunger valves were replaced later by two hollowjet valves.

Fig. 6a — 6-inch valve discharging with hood removed

This experience demonstrates the importance of edaquate instrumentation for investigating pressure fluctuations in a high-velocity jet. Sensitive pressure-cell measurements will indicate the frequency and maximum intensity of the pressure forces so that adequate support and steffening for structural members can be provided.

Fig. 6b — Pressure connections in hoods of 72-inch prototype valves

PROBLEMS IN STILLING BASINS

Glendo Dam Outlet Works[2)]

Glendo Dam is a multipurpose structure on the Bureau of Reclamation's Missouri River Basin Project, and is located on the North Platte River in southeastern Wyoming. Normal releases for irrigation and power pourposes are made through a *23*-foot-diameter conduit which branches into two *12*-foot-diameter power penstocks and three *12*-foot-diameter outlet pipes. The outlet works has a desgn capacity of *10,000* cfs at a maximum head of *150* feet and is controlled by three regulating slide gates, each *7* feet *3* inches wide and *7* feet *9* inches high. Flow from the regulating gates which are tilted downward *15* degrees enter three *20*-foot-wide outlet bays separated by two intermediate dividing walls before entering a hydraulic jump stilling basin, Figure 8. The stilling basin is *66* feet wide and *72* feet long. Flow from the outlet works basin combines with the power-plant flow and enters a common outlet channel. When power is being generated, approximately *1—1/2* feet of additional tailwater is available at the outlet works stilling basin.

The outlet works structure is unusual in that the regulating gates are placed low relative to the tailwater and the stilling basin has a length of only *2.8* times the conjugate depth. Model studies conducted in *1954* indicated that comparatively large chute blocks and baffle piers were required to obtain adequate stilling basin action in the comparatively short basin length.

When the outlet works was placed in operation in the spring of *1958*, an audible thumping noise was noted in the stilling basin and vibrations were observed in the basin training walls, particularly the left wall which is cantilevered between the basin and powerplant tailrace. The thumping noise had no definite period; at times the »thumps« were barely audible and occurred at time intervals of *10* seconds; at other times, a flurry of thups would occur at one or two second time intervals and the louder thumps could be heard *100* feet from the basin. There appeared to be a direct relationship between

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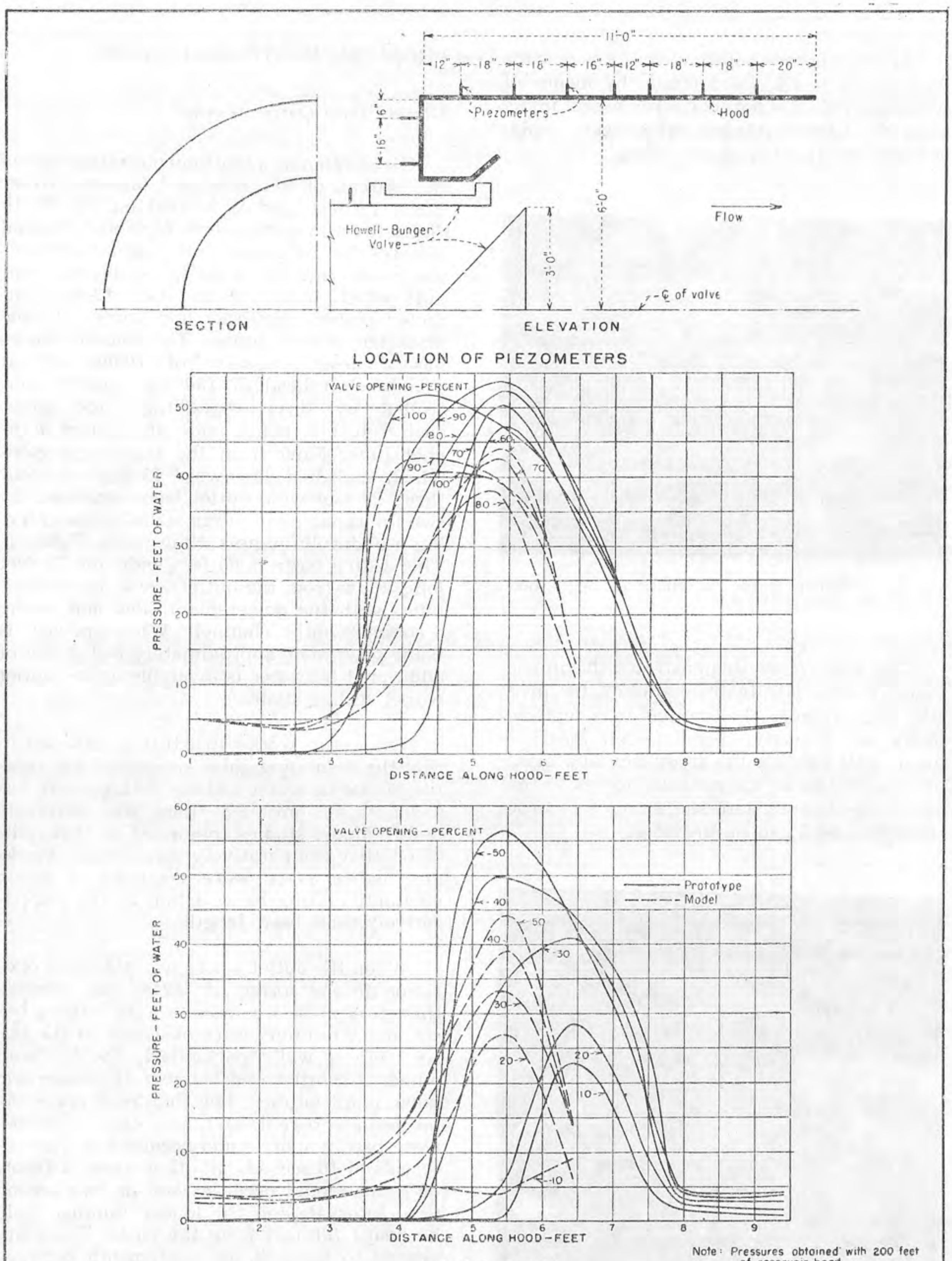
2) Bureau of Reclamation Report No. HYD-461, Hydraulic model studies of Glendo Dam Outlet Works-Missouri River Basin Project.

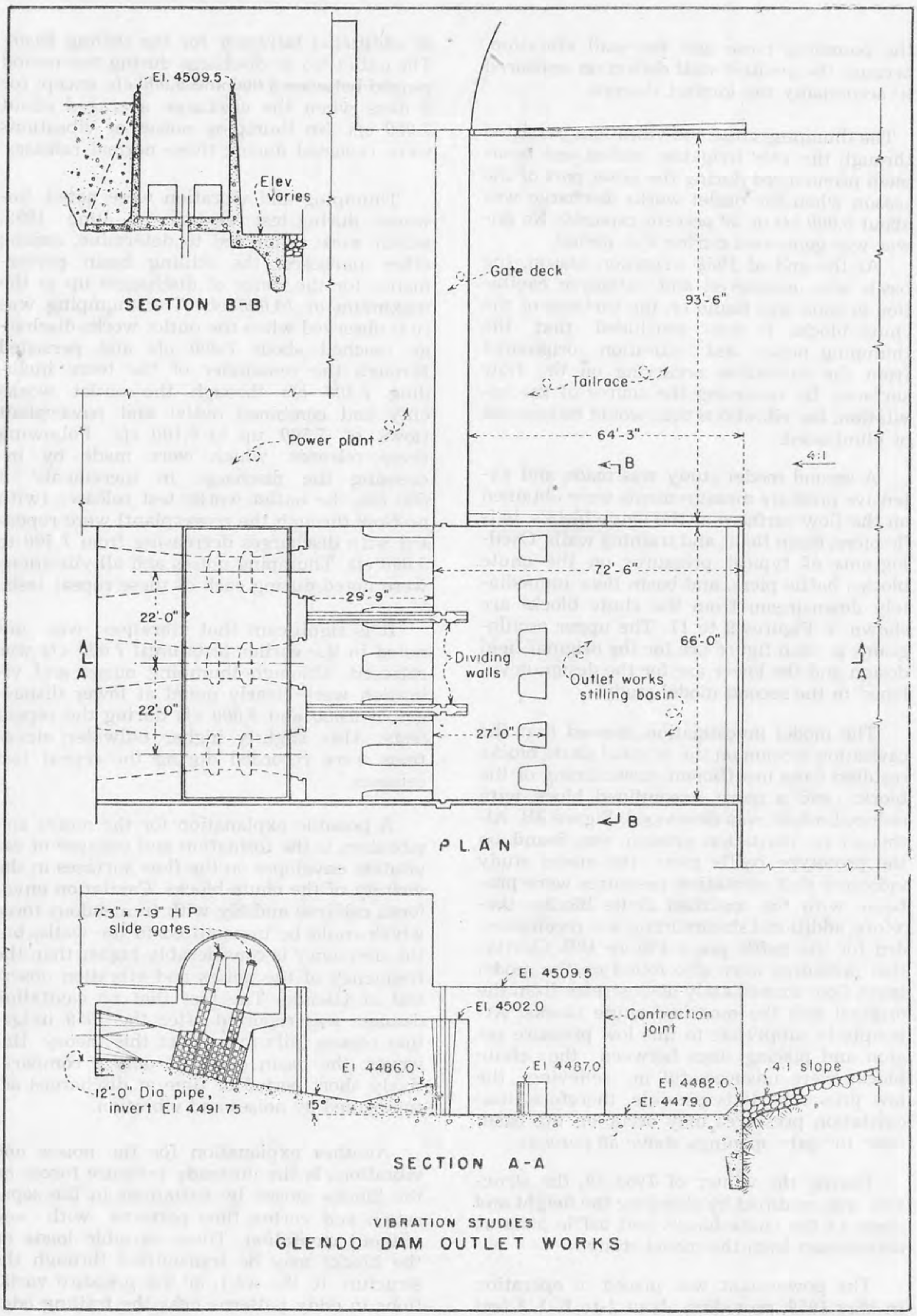


ROSS DAM

HOWELL-BUNGER VALVE HOOD-MODEL-PROTOTYPE
COMPARISON OF PRESSURES ON HOOD
FOR DIFFERENT VALVE OPENINGS

291

Fig. 7



El. 4509.5
Elev. varies
SECTION B-B
Gate deck
93'-6"
Tailrace
Power plant
64'-3"
4:1
B
B
72'-6"
29'-9"
22'-0"
A
A
Dividing walls
Outlet works stilling basin
22'-0"
27'-0"
66'-0"
PLAN
7'3" x 7'-9" H.P. slide gates
El. 4509.5
El. 4502.0
Contraction joint
El. 4486.0
El. 4487.0
4:1 slope
El. 4482.0
El. 4479.0
12'-0" Dia. pipe, invert El. 4491.75
15°
SECTION A-A
VIBRATION STUDIES
GLENDO DAM OUTLET WORKS

Fig. 8

the pounding noise and the wall vibration, because the greatest wall deflection appeared to accompany the loudest thumps.

The thumping noise and vibrations persisted through the *1958* irrigation season and becamem pronounced during the latter part of the season when the outlet works discharge was about *5,000 cfs* or *50* percent capacity. No power was generated during this period.

At the end of *1958* irrigation season, the basin was unwatered and extensive cavitation erosion was found on the surfaces of the chute blocks. It was concluded that the thumping noises and vibration originated from the cavitation occurring on the flow surfaces. By removing the source of the cavitation, the vibrations thus would be reduced or eliminated.

A second model study was made and extensive pressure measurements were obtained on the flow surfaces of the chute blocks, baffle piers, basin floor, and training walls. Oscillograms of typical pressures on the chute blocks, baffle piers, and basin floor immediately downstream from the chute blocks are shown in Figures 9 to 11. The upper oscillograms in each figure are for the original field design and the lower are for the design developed in the second model study.

The model investigation showed that the cavitation erosion on the original chute blocks resulted from insufficient streamlining of the blocks, and a more streamlined block with reduced height was developed, Figure 9B. Although no cavitation erosion was found on the prototype baffle piers, the model study indicated that cavitation pressures were probable with the modified chute blocks; therefore, additional streamlining was recommended for the baffle piers, Figure 10B. Cavitation pressures were also found on the model basin floor immediately downstream from the original and the modified chute blocks. Attempts to supply air to this low pressure region and placing steps between the chute blocks were unsuccessful in relieving the low pressures. It is possible, therefore, that cavitation pressures may occur on the basin floor for gate openings above *50* percent.

During the winter of *1958-59*, the structure was modified by changing the height and shape of the chute blocks and baffle piers as determined from the model study.

The powerplant was placed in operation in May *1959*, providing about *1-to 1—1/2* feet of additional tailwater for the stilling basin. The outlet works discharge during this period ranged between *3,000* and *5,000 cfs*, except for *6* days when the discharge averaged about *7,000 cfs*. No thumping noises or vibrations were reported during these normal releases.

Thumping and vibration were noted, however, during test releases in June *1959*, which were conducted to determine, among other purposes, the stilling basin performance for the range of discharges up to the maximum of *10,000* cfs. The thumping was first observed when the outlet works discharge reached about *7,000 cfs* and persisted through the remainder of the tests, including *7,500 cfs* through the outlet works only and combined outlet and powerplant flows of *7.500* up to *9,100 cfs*. Following these releases, which were made by increasing the discharge in increments of *500 cfs*, the outlet works test releases (with no flow through the powerplant) were repeated with discharges decreasing from *7,500* to *5,000 cfs*. Thumping noises and all vibrations were noted during each of these repeat tests.

It is significant that vibration was not noted in the earlier tests until *7,000 cfs* was released, although thumping noises and vibration were clearly noted at lower disharges of *6,000* and *5,000 cfs* during the repeat tests. Also, slightly higher tailwater elevations were recorded during the repeat test releases.

A possible explanation for the nosies and vibration is the formation and collapse of cavitation envelopes on the flow surfaces in the vicinity of the chute blocks. Cavitation envelopes collapse audibly with tremendous force which could be transmitted to the walls, but the frequency is considerably higher than the frequency of the noises and vibration observed at Glendo. The fact that no cavitation damage was reported after the *1959* irrigation season fails to support this theory. However, the basin operated only a comparatively short period of time at discharges accompanied by noises and vibration.

Another explanation for the noises and vibrations is the unsteady pressure forces on the blocks caused by variations in the separation and vortex flow patterns with and without cavitation. These variable loads on the blocks may be transmitted through the structure to the wall; or the pressure variations in eddy patterns near the trailing edge

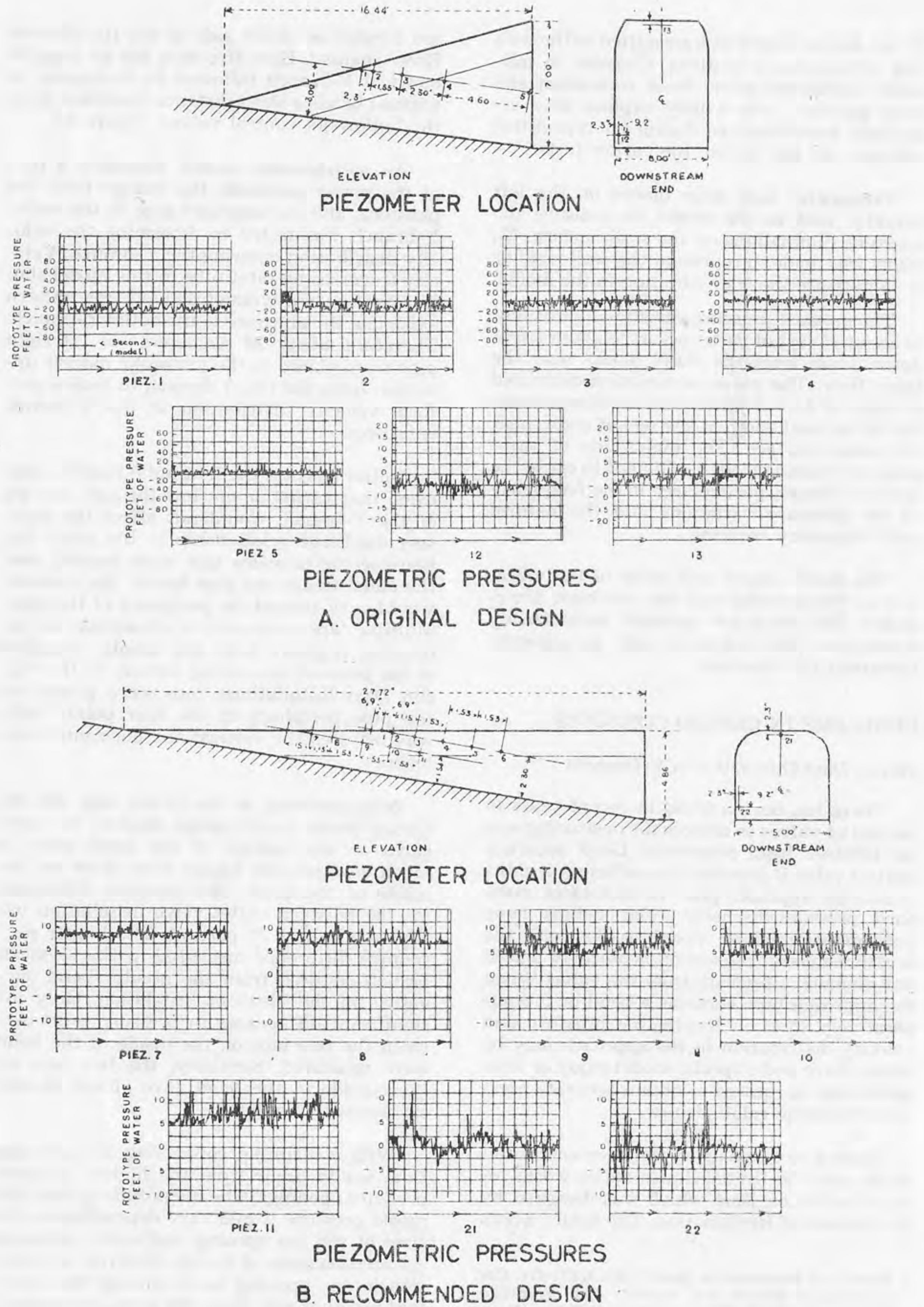

ELEVATION
DOWNSTREAM END
PIEZOMETER LOCATION
PROTOTYPE PRESSURE FEET OF WATER
Second (model)
PIEZ. 1
2
3
4
PIEZ. 5
12
13
PIEZOMETRIC PRESSURES
A. ORIGINAL DESIGN
ELEVATION
DOWNSTREAM END
PIEZOMETER LOCATION
PIEZ. 7
8
9
10
PIEZ. 11
21
22
PIEZOMETRIC PRESSURES
B. RECOMMENDED DESIGN

Fig. 9

of the blocks might be transmitted to the wall and initiate the vibrations. Changes in tailwater elevations affect these separation and eddy patterns, which may explain why vibrations were observed during the repeat test releases and not during the earlier tests.

Piezometer taps were placed on the left training wall in the model to measure the pressure fluctuations on the wall surface. No effort was made to represent the wall rigidity or to measure the wall vibration in the model.

The greatest pressure variation, equivalent to about *45* feet of water occurred about *3* feet downstream from the chute blocks near the basin floor. The pressure variation decreased to about *20* feet of water near the downstream end of the wall and to a few feet of water near the water surface. The magnitude of these pressure variations was sufficient to cause the wall to vibrate, particularly if the frequency of the pressure variations and the natural wall frequency coincide.

The direct source and cause of the vibration in the training wall has not been determined. The structure operated satisfactorily during the *1960* irrigation with no apparent thumping or vibration.

PROBLEMS IN CLOSED CONDUITS

Falcon Dam Outlet Works Y-Branch[3)]

There has been a trend in recent years to use outlet valves as devices for measuring water releases from reservoirs. Good accuracy control valve is preceded by sufficient lengths of straight approach pipe. In such cases, standard pressure-discharge relationships have been determined by model studies with the pressure-measuring section arbitrarily placed one diameter upstream from the valve. When the approach pipe contains a bend or is comparatively short in length, the pressure and velocity distribution in the approach may be nonuniform and a special model study or field calibration is rquired to obtain accurate pressure-discharge relationships.

Such a case exists at the Mexican outlet works and the United States outlet works located at Falcon Dam which was designed by the Bureau of Reclamation. The outlet works are located on either side of the Rio Grande River channel. Each structure has an unsymmetrical Y-branch followed by horizontal or vertical bends a short distance upstream from the hollow-jet control valves, Figure 12.

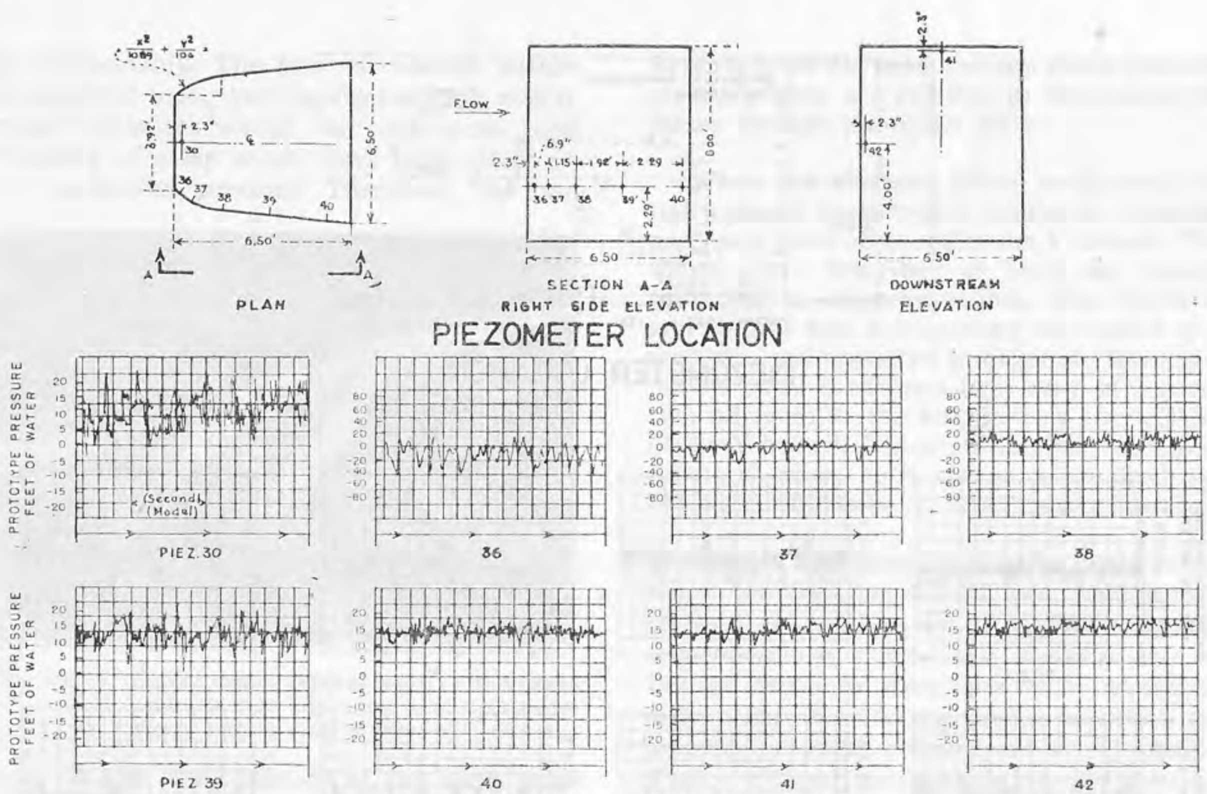
An aerodynamic model, including a part of the power penstock, the branch from the penstock, and the approach pipe to the outlet Y-branch was tested to determine the velocity distribution entering the Y-branch. Velocity traverses by pitot tube in this model showed that a very symmetrical valocity pattern existed at the entrance to the outlet Y-branch. Therefore, about *20* diameters of straight pipe were placed in the hydraulic models upstream from the two Y-branch to assure uniform velocity distribution at the Y-branch entrances.

Initial tests on the hydraulic models indicated that varied or no flow through one leg of the Y-branch would not affect the pressure-discharge relationship in the other leg. Because the pressure taps were located near the downstream end pipe bends, the pressure would vary around the periphery of the pipe. Multiple taps connected to a manifold for indicating pressure head are usually installed at the pressure measuring section. At the Falcon Dam installations, taps were placed on the pipe periphery at the four points midway between the vertical and horizontal centerlines.

Measurements at the model taps for the United States outlet valves showed the pressures on the outside of the bend were as much as *4* percent higher than those on the inside of the bend. The pressure difference for the Mexican outlet valve installation varied as much as *31* percent. The higher percentage difference measured in the Mexican branch resulted from the greater bend curvature in the Mexican instalation. Only insignificant differences in pressure head between the two taps on the inside of the bend were measured. Similarly, the two taps on the outside of the bend gave almost identical pressure readings.

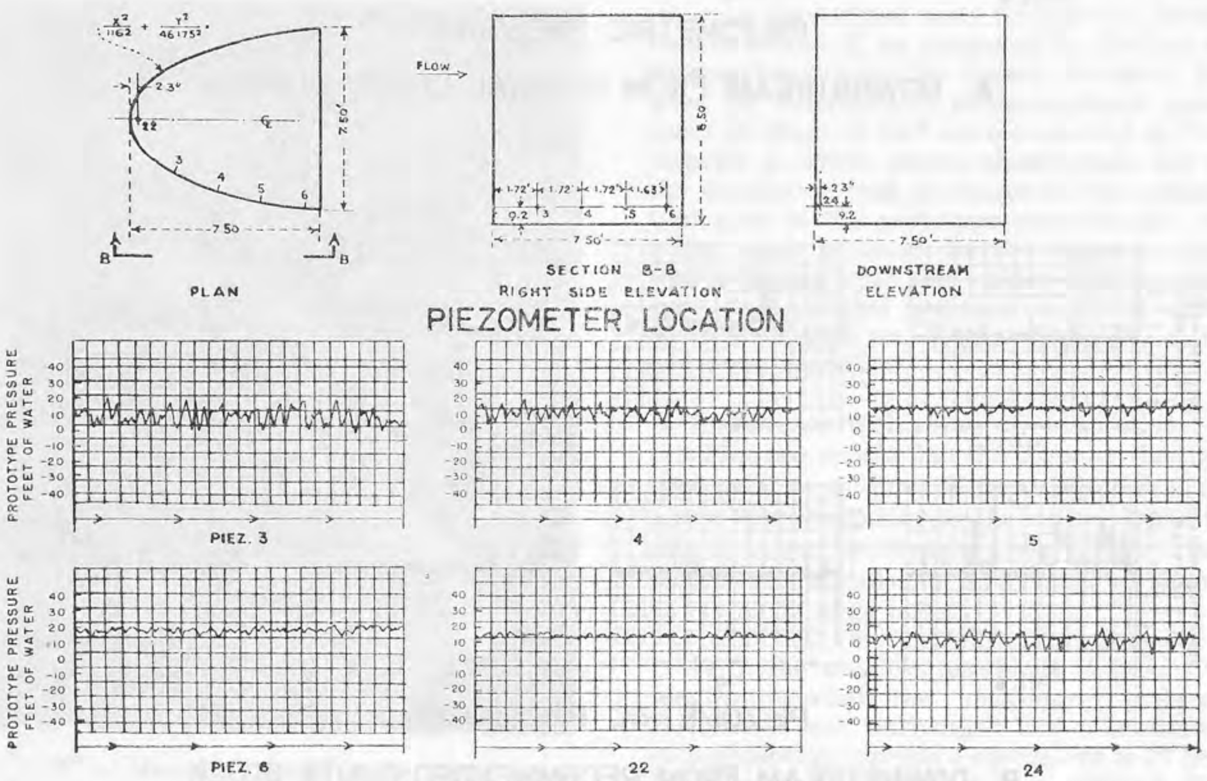
With a manifold connecting all four taps flow would occur from the higher to lower pressure openings. The magnitude of this manifold pressure would vary depending on the sizes of the tap opening and water passages. An accumulation of foreign material or corrosion in any opening would change the manifold pressure and, thus, the pressure-dischar-

3) Bureau of Reclamation Report No. HYD-474, Calibration of Hollow-Jet Valves and Vibration Studies of Outlet Works Y-Branch-Falcon Dam.



PIEZOMETRIC PRESSURES

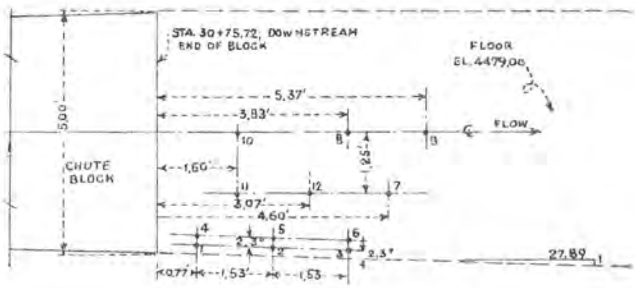
A. ORIGINAL DESIGN



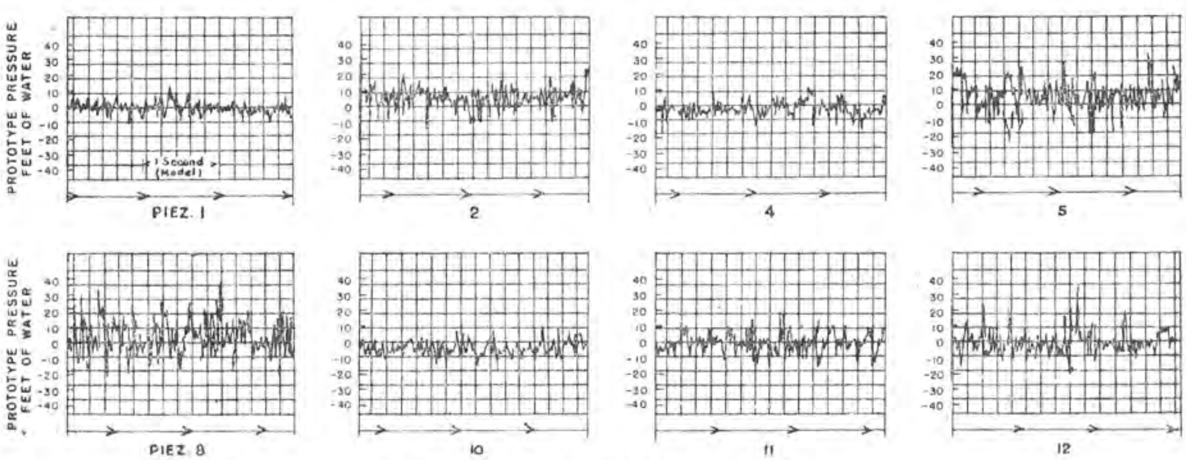
PIEZOMETRIC PRESSURES

B. RECOMMENDED DESIGN

Fig. 10

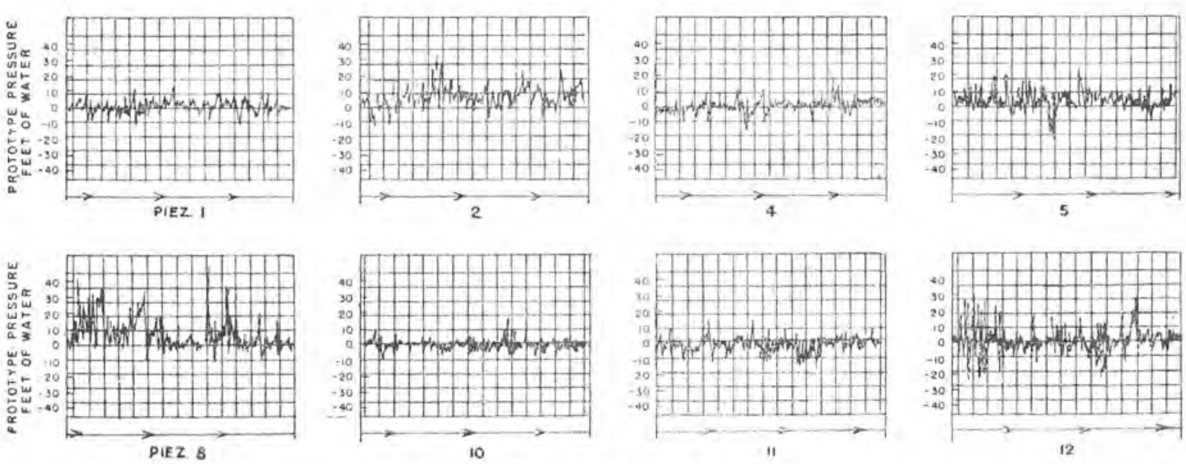


PIEZOMETER LOCATION



PIEZOMETRIC PRESSURES

A. DOWNSTREAM FROM ORIGINAL CHUTE BLOCK



PIEZOMETRIC PRESSURES

B. DOWNSTREAM FROM RECOMMENDED CHUTE BLOCK

Fig. 11

ge relationship. The flow circulation within a manifold using two taps measuring nearly equal pressures would be negligible and blocking of a tap would have little effect on the measured pressure. Therefore, the two

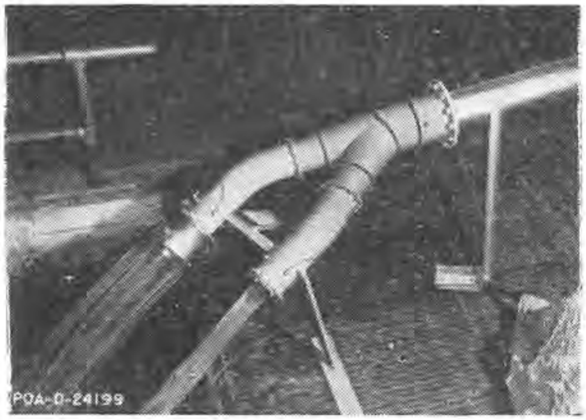


Fig. 12a — United States Outlets Right Outlet Complete Orifice replacing left hollow-jet valve Model scale 1 : 12

taps on the outer surface of the bend were used in the prototype installation because heads of greater magnitude were involved, resulting in more accurate recordings of head.

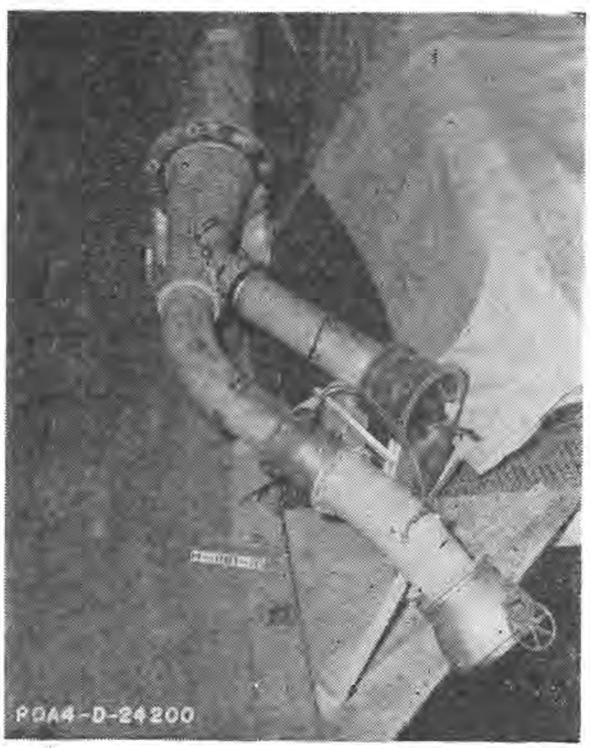


Fig. 12b — Mexican Outlets Right Outlet Complete Left outlet - - Laboratory control valve in position of left butterfly valve Model scale 1 : 15

Reports from the field indicate these pressure measurements are reliable in measuring releases through the outlet works.

When the Mexican outlet works was initially placed in operation, excessive vibration and noise were observed in the Y-branch. The noises were described as loud and heavy thumping or slapping sounds. The vibration and sounds had a frequency of from *2* to *3* secondes and appeared to originate from turbulent eddy conditions in a zone of separation adjacent to the left wall of the left leg of the Y-branch. The condition was more pronounced when both valves were discharging simultaneously at large valve openings.

Similar vibration tendencies were noted when the flow conditions were represented in the *1 : 15* scale model of the Y-branch and control valves, Figure 12B. Because the vibration and noise were apparently associated with highly fluctuating pressures within the branch, numerous piezometers were installed, Figure 13, and measurements of transient pressures were made with strain-gage-type pressure cells and recorded by oscillograph.

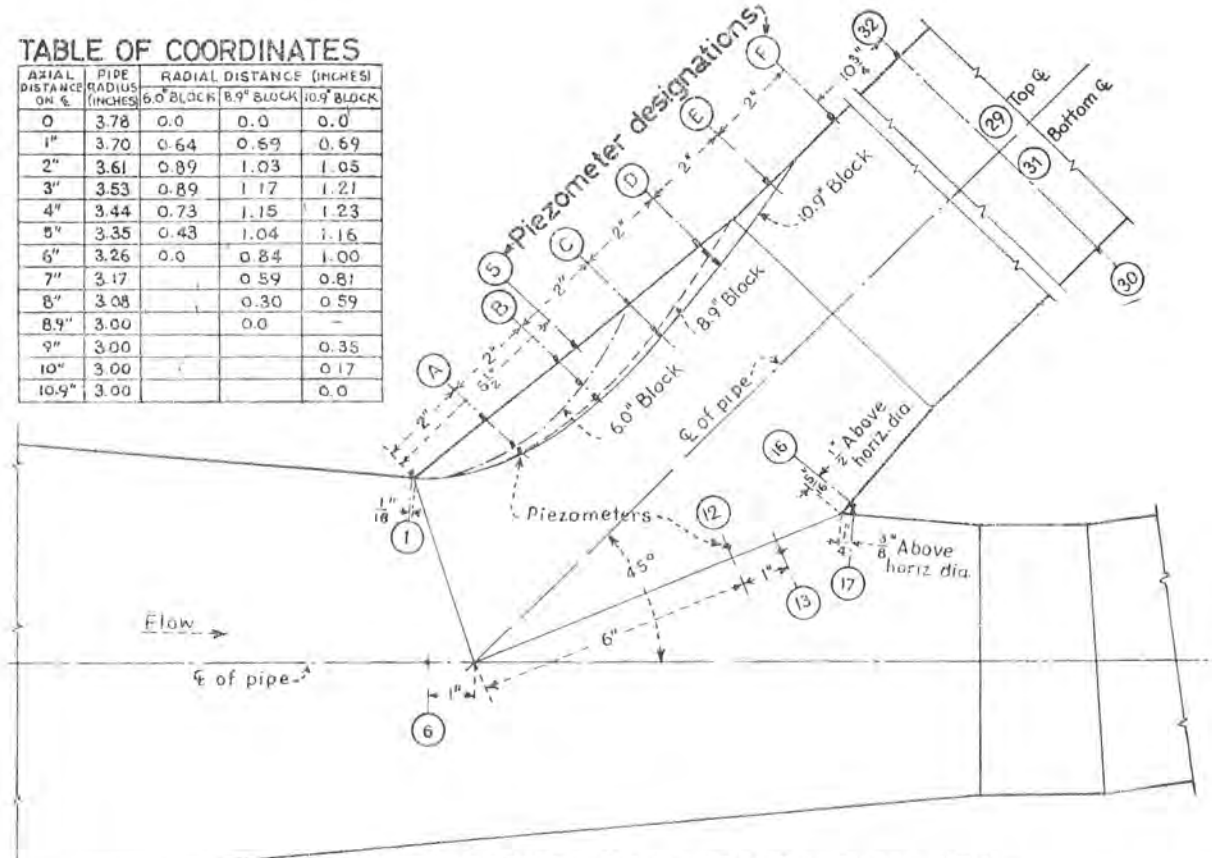
Rapid pressure fluctuations up to *60* feet of water (prototype) were recorded at Piezometers *D* and *E*, as compared to *4.0* feet at Piezometer *1* near the branch entrance, Figure 14. Intermittent subatmospheric pressures of about *17* feet were measured at Piezometer *5*. These model observations led to the conclusion that pressures in the separation zone of the prototype momentarily reached vapor pressure, formed vapor cavities that collapsed with the sudden rise in pressure, and initiated pressure surges of sufficient magnitude and frequency to cause the noise and vibration.

Experience with zones of separation of this type has shown that the pressure fluctuations will be minimized by roughly shaping a new flow boundary to the outher limits of the turbulent separation zone. Three filler blocks with dimensions and shapes as shown in Figure *13* were tested.

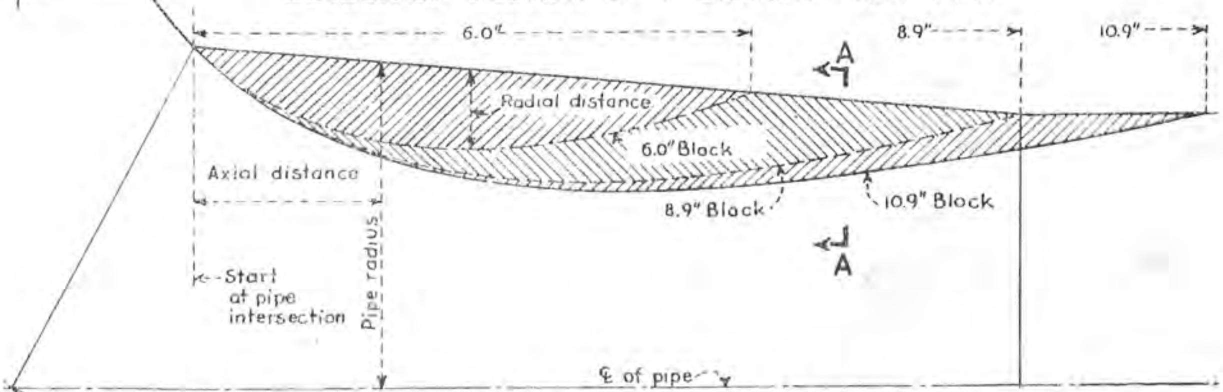
With the smallest test block *(6* inches in length) installed, the maximum pressure fluctuation was unchanged and a minimum subatmospheric pressure equivalent to *27* feet of water was observed at Piezometer *3*. The intermediate filler block *(8.9* inches) reduced the pressure fluctuations to a maximum of *20*

TABLE OF COORDINATES

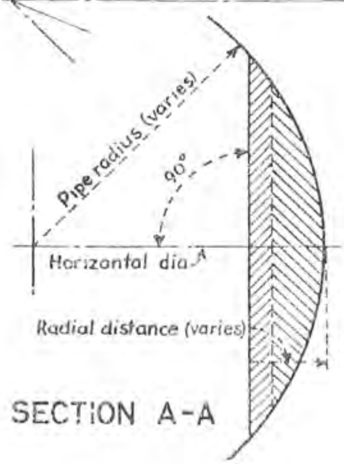
AXIAL DISTANCE ON ℄	PIPE RADIUS (INCHES)	RADIAL DISTANCE (INCHES) 6.0" BLOCK	8.9" BLOCK	10.9" BLOCK
0	3.78	0.0	0.0	0.0
1"	3.70	0.64	0.69	0.69
2"	3.61	0.89	1.03	1.05
3"	3.53	0.89	1.17	1.21
4"	3.44	0.73	1.15	1.23
5"	3.35	0.43	1.04	1.16
6"	3.26	0.0	0.84	1.00
7"	3.17		0.59	0.81
8"	3.08		0.30	0.59
8.9"	3.00		0.0	—
9"	3.00			0.35
10"	3.00			0.17
10.9"	3.00			0.0



DEVELOPED SECTION OF Y-BRANCH-PLAN VIEW

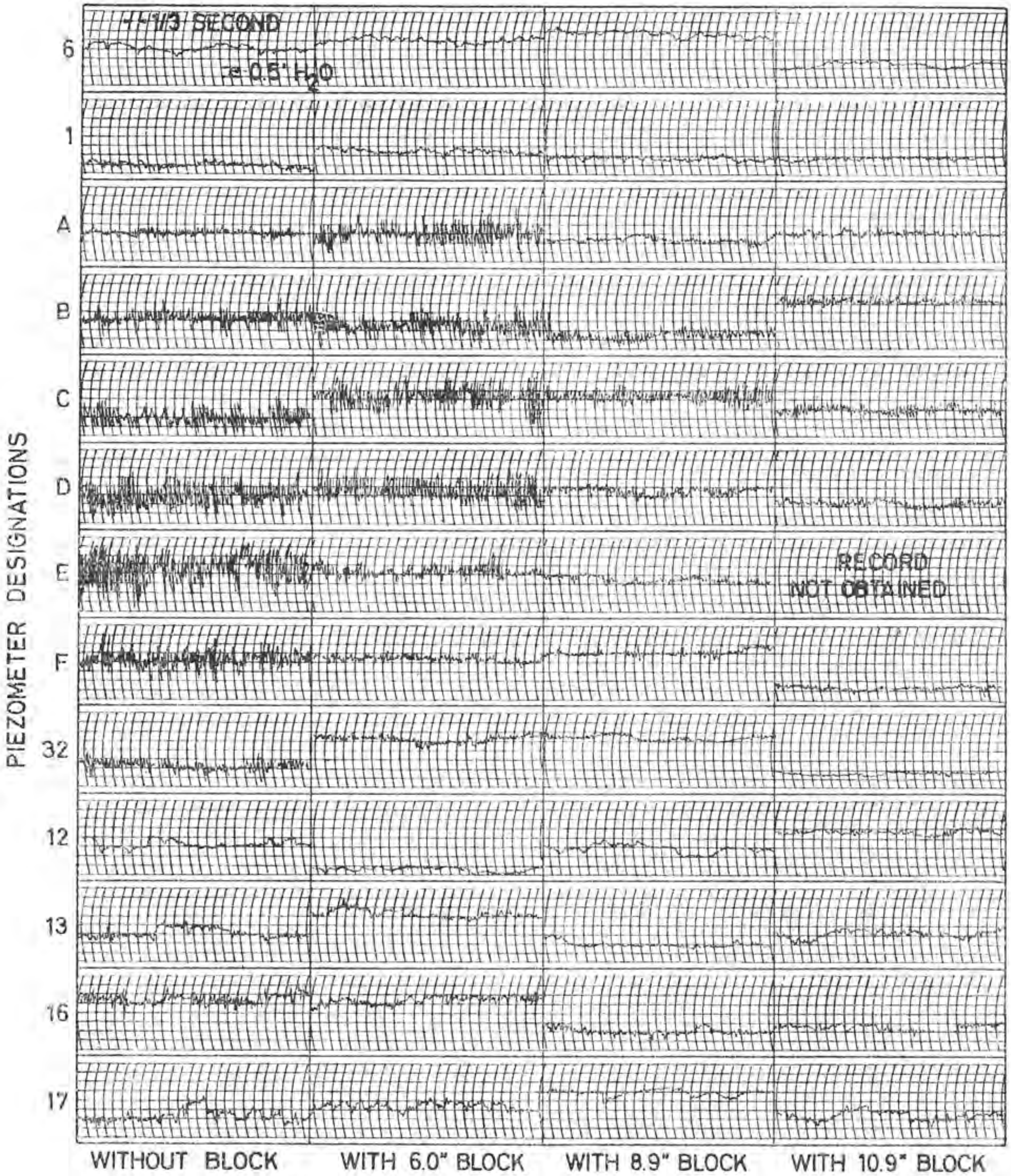


ENLARGED SECTION OF BLOCKS



SECTION A-A

Fig. 13



Horizontal scale:-lines at 1/3 second intervals,
Vertical scale:-heavy lines at 0.5' H_2O model intervals

NOTES

See Figure 4 for piezometer locations and block shapes.
Both 90-inch hollow jet valves fully opened-maximum head.
Rate of flow-6.68 c.f.s. (5 820 c.f.s. prototype)

Fig. 14

feet and the lowest observed pressure was 7 feet of water at Piezometer *C*. Installation of the largest test block (*10.9* inches) resulted in a negligible decrease in the pressure fluctuations from those on the intermediate size.

It was concluded that the intermediate-sized filler block gave optimum pressure conditions and the field structure was modified to include this shape.

Subsequent observations on the field structure indicated the restrictive flow boundary eliminated the heavy thumping sounds and vibration in the Y-branch, suggesting a substantial reduction in pressure fluctuation.

CONCLUSIONS

Adequate investigation of zones of turbulent eddies is emphasized for studies of structures involving high-velocity flow. The capabilities and limitations of test equipment must be determined. Maximum benefit from basic and applied studies is obtained through analysis of accurate and reliable measurements of the hydrodynamic forces in critical flow regions of the structure. Such test results from a model can be applied quantitatively and qualitatively to predict the operation of the prototype structure.

ACKNOWLEDGMENTS

The studies of turbulence and its effect on various types of hydraulic structures cited in this paper were carried out over a period of *10* years. Bureau of Reclamation Engineers Donald Colgate, Fred Locher, Jack C. Schuster, William P. Simmons, and William E. Wagner were the principal investigators for the design studies described in the laboratory reports referenced throughout the paper.